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HEARING[1,2]

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Over 500 publications on hearing appeared in the last year. It would take almost exactly the space of this chapter to list them. That might be the best way to use the space if it were not for the fact that the Psycho-Acoustic Laboratory is bringing up to date the *Bibliography in Audition* (63). Since that work will fulfill the bibliographic function, this chapter will confine itself to a few major topics on which particularly significant work has been done in the last year: (*a*) the action of the cochlea, (*b*) detection and discrimination, (*c*) subjective attributes of sound, and (*d*) the hearing of speech and complex, speechlike sounds.

THE COCHLEA

In a sense, the study of the action of the cochlea is not psychology. The experimental work is done mainly by physicists and electrophysiologists, and the theorists are principally physicists and communications engineers. Yet the important problems in the psychology of hearing reduce, in large part, to questions about the action of the cochlea. A few recent papers have done much to consolidate our ideas about the mechanical analysis made by the cochlea and, thereby, to lay a groundwork for study of further stages of the process of hearing. Consequently, this chapter starts with, and considers at some length, recent developments in the field of that small organ.

Mathematical theory of the action of the cochlea.—Békésy's[3] observations on the physical properties and the mechanical action of the cochlea provided: (*a*) a picture of a mechanism sufficiently clear to suggest a differential equation, (*b*) measurements of the independent variables precise enough to permit numerical computation, and (*c*) measurements of the dependent variables sufficiently definitive to check a theoretical solution. Several theorists have taken advantage of this opportunity. The most recent developments constitute perhaps the culmination of one phase, the exploitation of a particular differential equation.

The equation (a hydrodynamical form of the telegrapher's equation

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[1] The survey of the literature to which this review pertains was completed in May, 1952.

[2] The preparation of this chapter was supported in part by a contract between the Air Force Cambridge Research Center and Massachusetts Institute of Technology.

[3] Békésy's observations were described first in European journals. In 1947, two of the most important papers were republished, in English, in the *Journal of the Acoustical Society of America*. Now, essentially the whole story is available in English in Chapter 27 of the new *Handbook of Experimental Psychology* (11).

that describes the propagation of a signal along a line consisting of distributed impedances) is the basis of the more-or-less independently constructed theories of Ranke (74, 75), Zwislocki (91, 92), Peterson & Bogert (66), and Fletcher (33). Since Ranke has considerably revised his earlier treatment (72, 73), it is probably fair to consider Zwislocki's 1948 paper the first of the current theories. Zwislocki gave a complete formulation of the action of the cochlea, but he assumed that the length of the wave that travels down the cochlea is long relative to the transverse dimensions of the cochlea, which is the case up to about 4000 c.p.s., and he simplified the computation by neglecting mass, which he regarded as playing a minor role. Then Peterson & Bogert (66) set up the problem somewhat differently, retaining the assumption of long wave length but neglecting friction instead of mass. And then Ranke's (74) revised theory appeared, giving a treatment of short waves as well as long ones and, if my understanding is correct, taking into account all three forms of impedance, but in a somewhat devious way.

From one point of view, the contribution of recent months has been the solution of the problem of how to take all three forms of impedance into account simultaneously and directly in the application of the fundamental dynamic equation. First, Bogert (18) obtained a solution by building an electrical analogue of the hydrodynamic model. The analogue was a cascade of 175 sections, each consisting of inductors, capacitors, and resistors chosen to mimic the values of mass, stiffness, and viscosity measured by Békésy. The behavior of the model in response to voltages impressed upon its "stapes" was strikingly similar to that of the human ear in Békésy's observations, and it differed in the expected way from the behavior of the frictionless (i.e., resistanceless) model of Peterson & Bogert. Then Fletcher (33) worked through the computations numerically, with mass, stiffness, and friction all in the picture. His solutions are in excellent agreement with curves shown by Békésy for the velocity of the traveling wave, the positions of maximum response, etc.

From another point of view, however, it appears that the contribution of recent months is to show how different can be rival formulations that start from the same physical measurements, employ the same fundamental equation, and check well with the same empirical observations.[4] Although

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[4] When it comes to checking against Békésy's observations, the situation is not as clear as I have implied. Actually, Békésy presented two sets of curves for one of the most basic functions, the one relating displacement amplitude to position along the cochlear partition. [Originally, they appeared in different papers, but they can be seen in Figures 32 and 35 of reference (11).] The two sets of curves are very different in a most important respect: the spread of response along the length of the cochlea is about three times as great in one as in the other. Phase curves are presented only with the narrow displacement-amplitude curves. A complete set of frequency-selectivity curves is presented only with the broad displacement-amplitude curves. Zwislocki chose the frequency-selectivity curves (broad) against which to check his theoretical calculations, whereas Fletcher's calculations yield curves that approximate Békésy's

there are many features in common among Zwislocki's, Peterson & Bogert's, Ranke's, and Fletcher's formulations, there are important differences. These lie in associating aspects of the actual situation with variables in the model. As Fletcher puts it,

> Although the fundamental differential equation which is used is the same as that used by Peterson and Bogert and Zwislocki, except for a term involving the viscosity of the fluid, the interpretation of the constants and the boundary conditions are very different. (33, p. 637.)

In so far as there is—despite the differences of interpretation—consensus on general features, the current theory of the action of the cochlea (as I understand it) holds that: The acoustic (stimulus) pressure wave acts upon the normal ear principally through the drum skin and ossicular chain, which it sets into mechanical vibration. The vibration of the footplate of the stapes moves the fluid of the cochlea. The movements of the fluid are compression-rarefaction waves (I shall call them simply compression waves), but the fluid is so nearly incompressible that the vibration is propagated at extremely high velocity (approximately the velocity of sound in water) and therefore reaches all parts of the cochlea almost in the same phase. The compression waves set up vibration in a system consisting of the cochlear partition and fluid on either side of it. The coupling between the compression waves in the fluid and the partition-fluid system occurs principally, or almost entirely, in the base of the cochlea where the partition is stiff. In this basal part of the cochlea, all the segments (into which the partition is, for convenience, conceptually divided) vibrate together in essentially the same phase. From this part, the vibrations travel up the partition-fluid system, which acts as a transmission line. Energy flows from one segment to the next, principally through the fluid and not to any great extent through the partition itself.

The passage of the traveling wave along the partition-fluid system is very different from the passage of the compression wave through the fluid. The traveling wave is governed by the differential equation that serves as the common basis for the current theories. The frequency-selective action of the cochlea is due to the nonuniform distribution of impedances along the partition-fluid transmission line. The response of the cochlea to any stimulus is calculated by determining, for that stimulus, the difference in pressure (as a function of time) between the fluid near the oval window and fluid near the round window, and using that difference as a boundary condition for the differential equation. At the same time, of course, it is necessary to "plug in" the values of the impedances from Békésy's measurements, ter-

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narrow displacement-amplitude curves. When Huggins and I were working on the problem of sharpening mechanisms (44), we asked Békésy which of his two sets of curves was the more representative. His recollection was that the set with broad maxima was some kind of an average, whereas the set with sharp peaks was from a single, and somewhat unusual, preparation. However, Békésy had continually improved his technique, and the single preparation was one of his last ones in Europe.

minating the line with an impedance characteristic of the helicotrema.

Transmission-line theory versus parallel-resonator theory.—Against the interpretation just described, it is necessary to set an argument developed by Wever & Lawrence (89). Their picture of the action of the cochlea is a modern version of the classical resonance theory associated with Helmholtz. They start with the compression wave that passes at high velocity through the fluid of the cochlea. Instead of influencing primarily the stiff part, i.e., the basal turn, this compression wave acts directly upon all the segments of the cochlear partition. The coupling of these segments, one to another, is negligible, and each responds in a manner conditioned by its own resonance (its local impedance) and by the pressure difference produced across it, between the neighboring fluids in the vestibular and tympanic canals, by the compression wave. The essential feature is that there are, conceptually, many parallel resonators, all driven almost simultaneously (because of its high velocity of propagation) by the compression wave. This is basically different from the situation postulated by the traveling wave theories because, according to them, the compression wave acts chiefly on one part (the basal end) of the cochlear partition, and the principal component of the action of the rest of the partition is due to the passage of the traveling wave down the partition-fluid system, which if it is viewed as consisting of resonators, consists of many elements in cascade and not in parallel.

The evidence considered critical against the traveling wave theories by Wever & Lawrence is the following: They introduced sinusoidal vibrations into both ends of the cochlea and adjusted the amplitudes and phases until there was complete cancellation in the microphonic recorded from a particular location. Then, moving the active electrode, they found that there was complete or near complete cancellation also at all other locations. This could not be the case if waves traveled from opposite ends of the cochlea and passed in the middle unless the waves were of nonnegligible magnitude only in a very short segment. Wever & Lawrence also measured the time required for a sound put in at one end of the cochlea to come out the other, and they found that it was very short, far too short for a slowly traveling wave.

Fortunately for the traveling wave theories, it is possible to show that neither of Wever & Lawrence's items of evidence is at all critical. According to the traveling wave theories, the compression wave influences the stiff basal part of the cochlear partition, and the traveling wave travels from that part. This is the case no matter at what location in the cochlea the vibratory force is applied, as Békésy (6) showed clearly with both models of the ear and human cochlear preparations. The interpretation of the cancellation experiment is therefore simple and direct. The vibrations applied at the two ends of the cochlea were adjusted until their contributions to the pressure difference across the basal part of the partition cancelled. There was then no traveling wave, and therefore no microphonic response. The interpretation of the velocity measurements is even simpler, for the velocity measured was the velocity of the compression wave. According to all the theories, it goes approximately with the speed of sound in water. The important thing is not to get it mixed up with the slowly traveling wave to which it gives rise.

It is easy thus to dismiss the alleged evidence against the traveling wave theories, but doing so does not dismiss the parallel-resonator picture of the cochlear process. The pressure difference across each segment of the cochlear partition does of course act upon that segment, and that segment does of course respond in the way determined by the impedance presented to the driving pressure. The question is, to what extent is the driving pressure associated with the compression wave that reaches all parts of the cochlea almost simultaneously, and to what extent is it due to the traveling wave that passes more slowly along the partition-fluid transmission line.[5]

A direct and almost unambiguous answer to that question is given by observations made by Békésy (7). Békésy applied a very short pulse of sound to the oval window and, under stroboscopic illumination, watched the displacement of the cochlear partition at various distances from the oval window. He saw a moving wave of displacement, a traveling bulge. It started out with unmeasurably high velocity in the basal turn, for, as we have noted, the stiff basal part of the partition vibrates essentially as a whole. Then, as it continued along the cochlear spiral, it decelerated markedly. It reached the twentieth millimeter in about 1/5 msec., the twenty-fifth millimeter in about 1 msec., and the thirty-third millimeter in about 5 msec. No movement of any sort was visible at the apical end of the cochlea until the traveling bulge reached it. That, of course, is precisely the behavior that the traveling wave theory requires. And it is not at all what the parallel-resonator theory says should happen. The only way to rationalize it, I think, is to argue that Békésy did not see the start of the displacement, as he reported he did, but, instead, perceived displacement only when the actual displacement was nearly maximal. On that basis, even though all the parallel resonators were set into motion at the same instant, he would have seen the high-frequency basal elements move first, the low-frequency apical elements move only after a delay.

However, another set of observations of Békésy's (9) cannot be brought into line with the parallel-resonance theory by any rationalization. These are the observations of the phase of the displacements produced by sustained sinusoidal excitation. For frequencies of 200 c.p.s. and higher, Békésy measured phase shifts from the base to the apex of the cochlea that were as great as 400° or 500°. But, if the resonant elements postulated by the parallel-resonator theory are simple resonators, the phase shift between one end

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[5] Békésy points out, in personal communication, that actually the question is complicated by the fact that there are four, or perhaps five, kinds of waves that can, and probably do, exist to some extent in a system like the cochlea. In his opinion, rapid damping of the others is responsible for the fact that only one kind of wave (the traveling wave) is visible in the motion of the cochlear partition.

of the parallel array and the other is limited to 180°. And there is no way to conceive of the resonators as other than simple resonators, for, in a given segment, all the parts of the cochlear partition move in phase. Therefore, Békésy's phase observations constitute definitive evidence against the parallel-resonator theory and justification for adopting the general notion of the cochlear process expressed by the current traveling wave or transmission-line theories.

It is worthwhile noting how far the theory of the action of the cochlea worked out by Zwislocki (91, 92), Peterson & Bogert (66), Ranke, (72, 73) and Fletcher (33) takes us from the classical resonance theory. First, unless the term *resonance* is defined so broadly as to include almost any kind of frequency selectivity, the current formulations are not resonance theories. It is true that each segment of the cochlear partition is thought of as having a resonant frequency, but this resonance is not essential for the production of selective oscillation of the partition and, in fact, the maximum amplitude of oscillation does not occur at the segment for which the resonant frequency is equal to the stimulus frequency. It occurs, instead, at a point between the stapes and the resonant segment. Second, the analytic action of the cochlea is now thought of as due to the interaction of the parts of the partition-fluid system, and not to the local "sympathetic" vibrations of the separate parts of the basilar membrane. It is reasonable, therefore, to consider the timing of the oscillations of adjacent parts of the membrane as of very likely significance in the excitation of the neurons of the auditory nerve. This makes things more interesting than they were when the classical theory restricted attention to the amplitude of vibration. Third, the whole question of damping has taken on a new and different interpretation. In the old theory, damping was incompatible with sharp resonance, and sharp resonance was thought to be necessary for good frequency discrimination. Now, although the law relating the amplitude and phase response of a system to its transient response is with us just as much as ever, it is seen that, instead of leading of necessity to broad spread of activity within the cochlea, damping is in large part responsible for the frequency-selective action that does occur. In short, the reciprocal relation that exists between the time and frequency domains does not, in the current theories, imply a reciprocal relation between the time and place domains. And, fourth, the new theories are in principle much more powerful. It is now possible, at least in principle, to describe the behavior of the cochlear partition, not only in response to pure tones, but in response to any combination of tones or to any precisely defined vibratory input. This has become an important consideration during the last few years during which complex acoustic stimuli have displaced pure tones in the psychophysical study of hearing.

The unidirectional component(s) of the electrical response.—In 1950, Davis, Fernández & McAuliffe (27) reported the existence of a unidirectional potential in the electrical response of the ear, a wave with approximately the same form as the envelope of the familiar microphonic response. The

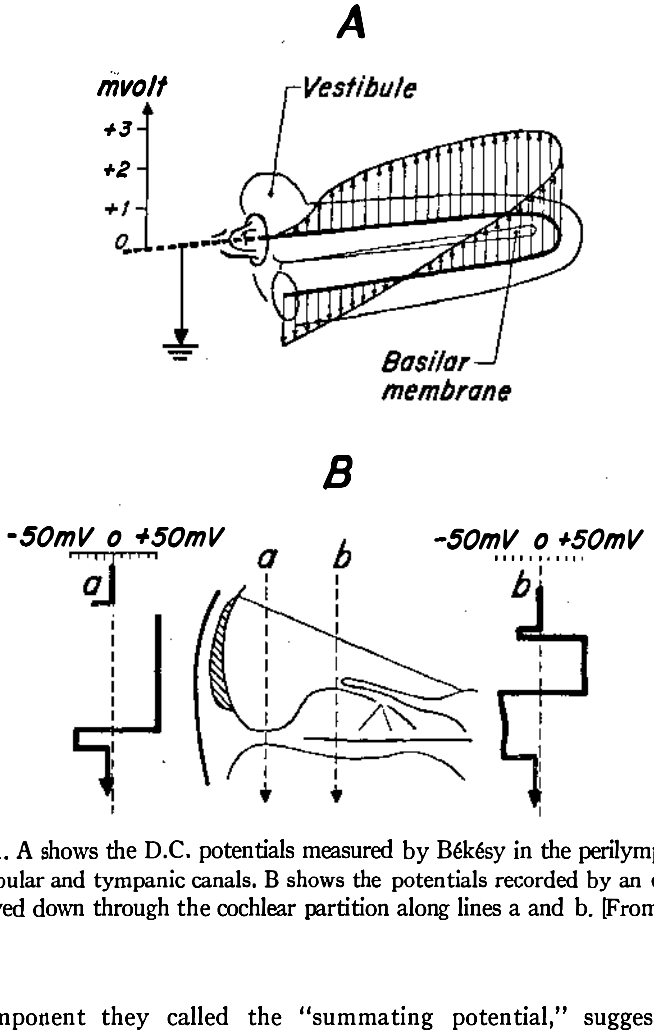

FIG. 1. A shows the D.C. potentials measured by Békésy in the perilymph along the vestibular and tympanic canals. B shows the potentials recorded by an electrode as it moved down through the cochlear partition along lines a and b. [From Békésy (10, 12).]

new component they called the "summating potential," suggesting an origin either in the excitatory process or in a microphonic process that plays a role in excitation. Independently, Lowy & Kemp (57) also observed a unidirectional (for short, D.C.) component.

Recently, Davis (26) and his co-workers found that the D.C. component reverses polarity when the guinea pig's oxygen supply is reduced, and reverses again if anoxia is allowed to progress. This suggests that the D.C. component may be made up of several parts. In Davis' current view, at least one of the parts may be neural in origin. If it is, it is either of unexpectedly short latency (0.12 msec. in one observation) or attributable to local potentials rather than nerve impulses.

The D.C. component, and the recorded nerve impulses and the A.C. microphonic as well, are influenced by the passage of a direct current through the segment of the cochlea from which they are recorded [Tasaki & Fernández (86)]. Whether the magnitudes are increased or decreased depends upon the direction of the D.C. flow.

Békésy, also, is working on a D.C. component. His D.C. component is clearly of microphonic, as opposed to neural, origin. It may or may not prove to be related directly to the potential recorded by Davis and his co-workers.

Békésy (10) measured, first, the relative potential levels of various points within the quiescent cochlea. He found, between a point near the stapes in the vestibular canal and other points in the vestibular and tympanic canals, the potential differences shown in Figure 1A. They are of the order of a millivolt. Then, entering the cochlear partition, Békésy (12) found much greater resting potentials. The variations in potential along two paths down through Reissner's membrane, through the endolymph, through the basilar membrane, and out into the tympanic canal, are shown in Figure 1B. Even in silence, the cochlear partition is electrically active.

Békésy's D.C. potential is influenced by acoustic stimulation. The D.C. potential difference between the round window and an indifferent electrode drops when a tone is turned on. If the tone is not too intense, the "D.C. fall" is proportional to the amplitude of the A.C. microphonic picked up by the same electrode on the round window.[6]

Békésy's observations bear on a question that has been debated for years. Does the microphonic response of the cochlea result from direct transduction of mechanical energy into electrical energy, or does it depend upon the release of energy, under the control of the stimulus, from sources within the cochlea? Two lines of evidence lead Békésy to conclude that the second alternative is correct.

First, if the energy of mechanical oscillation were transformed directly into electrical energy, a decrement in the appearance of electrical energy would have to be matched by a decrement in the disappearance of mechanical energy. But an experiment indicates that such is not the case. Suddenly lifting a tiny iron ball from Reissner's membrane sets the cochlear partition into transient oscillation. The electrical response is recorded before and after reduction of the oxygen supply to the guinea pig. The form of the damped wave is unaffected by the anoxia, but the amplitude is reduced to one-fourth its former value. The fact that the form of the damped wave is not changed indicates that the rate of disappearance of mechanical energy is still the same.

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[6] I have just seen the galley of another paper by Békésy (13). He first shows that Reissner's membrane and the basilar membrane effectively isolate the cochlear partition from the rest of the cochlea. He then measures both the D.C. and A.C. microphonic response with a fine electrode that moves downward through the cochlea, piercing the various membranes, cells, and ligaments. Except for the insulating membranes, all the components generate some electrical potentials. The first-order potentials, 5 to 10 times as large as the others, come, however, from a restricted source in the organ of Corti.

The fact that the amplitude is lower indicates that less energy is showing up in electrical form. *Q.E.D.*

Second, if one can demonstrate that more energy appears in electrical form than disappears from mechanical form, he can thereby destroy the possibility of direct transduction. Békésy did this by selecting the simplest case. He produced a static deformation of Reissner's membrane by pressing down on it with a needle, at the same time measuring the force on the needle and the displacement of the membrance so he could calculate the amount of mechanical work done on the system. On the electrical side, he measured the potential difference between two points in the cochlea separated by a known resistance. The deformation increased this potential difference and, therefore, increased the amount of electrical power being dissipated in the resistance—by a calculable amount. It turned out that the extra dissipation of electrical power, sustained for 1 sec., amounted to more energy than did the work done by the needle. Again, *Q.E.D.*

Finding that the process that produces the microphonic response is not passive does not mean that the action of the cochlea is not like that of a microphone. It means only that the cochlear microphone is not a passive microphone, is not—for example—like a piezoelectric crystal. A better analogue would be the recently developed vacuum-tube microphone: the vibration of the diaphragm is transmitted mechanically to the control grid of a vacuum tube, and the vibration of the grid modulates the flow of an electron current that is supported by a battery or power supply.

The space-time pattern of the microphonic response.—Tasaki, Davis & Legouix (85) recorded microphonics through differential leads, pairs of 20-μ electrodes inserted into the cochlea (one electrode in the vestibular canal, one in the tympanic), and found that pickup is restricted mainly to a segment of the cochlear partition about 1 mm. long. Using a number of such pairs of electrodes, they determined the amplitude and phase of the electrical response as a function of stimulus frequency and electrode location. Their measurements are relative (response in basal turn held constant by adjusting stimulus intensity), but in other respects they are directly comparable with Békésy's measurements of displacement. The qualitative features of the electrical picture are reasonably similar to those of the mechanical picture.

Electrical response of the auditory nerve.—The neural component of the electrical response to an acoustic click, picked up by an active electrode near the round window, is a complex phenomenon. Rosenblith & Rosenzweig (76) found that they could record it without contamination by microphonics if they placed the electrode in one of a number of locations that were, for the microphonic response to a click, null-response locations. Moving the electrode from one such location to another accented some parts of the neural response and attenuated others. Usually, the neural response consisted of two prominent spike-like parts.

McGill (58) and McGill & Rosenblith (59) studied the behavior of the first part of the neural click response, recorded at the round window, as a function of the intensity and polarity of the stimulus pulse and of the intensity of a conditioning pulse presented prior to the stimulus pulse by a variable interval. Their results led to the formulation of a statistical model. According to the model, the part of the response under study is the summated effect of essentially simultaneous discharges in many independent neural units, each of which has a threshold, an all-or-none response, and a recovery curve. By assuming two sets of neural units, one with a Gaussian distribution of thresholds and the other with an unspecified distribution, they accounted for the behavior of the response under the wide variety of conditions specified by their parameters.[7]

DETECTION AND DISCRIMINATION

Under this heading, which has been a main topic in the psychophysics of hearing, there is not in the work of the last year the material for a coherent story. There are, however, some interesting pieces:

The quantal nature of discrimination.—Corso (24) contributed another chapter to the debate on quantal discrimination. He determined psychometric functions for frequency and for intensity discrimination. In all, he obtained 70 functions, each based on roughly 1200 judgments. The critical questions were: (*a*) do the points fall along straight lines, and (*b*) is the smallest increment always reported just twice the largest increment never reported? Only 9 of the 70 functions passed the chi-square test of goodness of fit to the straight line, and only one of those came really close to the two-to-one ratio. Corso therefore rejected the quantum theory.

Taken at face value, Corso's procedure for arriving at a decision to reject the theory seems to be straightforward. However, we are left, I think, almost as we (probably) were beforehand: not convinced either way, and wondering what—unless it might be finding perfectly Gaussian or perfectly linear psychometric functions ourselves—might convince us. The difficulty is that the quantal model cannot be expected to hold if the observer's responses are influenced by noise, by change of set, by warming up or quieting down, or fatigue or boredom. Therefore, to disprove the theory, one must not only fail to get psychometric curves that meet the criteria, but he must convince his colleagues that he has squeezed all the nonphysiological error variance out of his measurements and has worked at the physiological limit. The finder of positive evidence, on the other hand, has an easier task, for most of us hope that things will turn out eventually to be simple, and seeing points fall neatly along a straight line makes us feel that we have had a good, clear look at the true mechanism in action. It is a shame that the quantum theory has such strong built-in self-protection.

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[7] With this brief section, we leave the mechanical and physiological studies on hearing. The middle ear we can dismiss with a note that Payne & Githler (65) have destroyed various parts and amounts of the drumskin and noted the effects upon the electrical response, and that Fletcher (34) has demolished the old theory, well recounted only recently by Lawrence (50), that the drumskin and ossicles constitute an effective impedance-matching transformer. Fletcher showed that our insensitivity at low frequencies is due very largely to the extreme inefficiency of those coupling components. Not much has been done in the last year on the lower centers of the auditory system. Studies on the medial geniculate body and the auditory cortex are covered in the chapter by Dr. W. D. Neff. (See pp. 255–257.)

Differential threshold for intensity.—Extending the work of Miller (60) and Harris (41), Pollack (69) determined the differential threshold for white noise as a function of the rate of alternation between the standard and comparison segments of the noise. As the rate of alternation increased, and therefore as the interval between the more intense segments ("bursts") decreased, the threshold remained constant at about 0.5 db until the interval between bursts was about 50 msec., whereupon the threshold started to increase. Pollack interpreted this fact as confirming Miller's conclusion (61) that it takes about 50 msec. for the activity, set up in the nervous system by white noise, to die down. At shorter intervals, the neural effects of one burst of noise pile upon the heels of the preceding burst and the fluctuations of intensity in the neural signal are less marked than they are when the intervals between bursts are longer. This, of course, would explain the change in the difference limen, for the stimulus differential would have to be increased to produce the same neural differential.

Differential threshold for frequency.—Harris (42) reported measurements of the influence on the differential threshold for frequency of the interval between the standard and comparison tones. This influence was surprisingly small, especially when the standard frequency remained fixed throughout the experiment. In that case, the threshold (about 4 c.p.s. at 1000 c.p.s.) was nearly independent of the interval for intervals from about 0.3 to 7 sec., and it was only a little over 7 c.p.s. at 25 sec. When the standard frequency was moved about in the range 950 to 1050 c.p.s., the threshold increased more rapidly as the interval was lengthened. It started near 4 c.p.s., reached 8 c.p.s. at about 15 sec.

These data add to the picture that has been taking form over a period of several years: the observer builds up a reference structure and judges with respect to it, not to the standard-comparison pair in isolation. The behavior of Harris' thresholds, the anchoring of "absolute" judgements, and possibly figural aftereffects and some phenomena of auditory "fatigue" reflect the dynamics—as yet by no means well understood—of that reference structure.

Masking.—It is a matter of some importance, for example in designing detection systems that employ aural presentation of signals to the operators, to know whether a listener gets, from a single presentation of a signal, almost all the information he is ever going to get out of that signal, or whether he can profit from repeated presentations. Schreitmueller (78) studied that question in a very simple case, the detection of a short segment of tone in the presence of random noise. He found that, when the same pulse was repeated n times, each time in precisely the same sample of noise, the optimal value of n for detection was 2. The percentage of 10-sec. trials in which anything was detected increased a little as n went from 1 to 2, but it decreased again when 4 or 6 or 8 of the 10 1-sec. intervals contained a pulse of tone. On the other hand, Schreitmueller found the more pulses the better when the successive samples of noise were different. Even though they were successive samples of a noise with contant statistical parameters, the samples were different enough for the listeners to take some advantage of the multiple presentation. The advantage of eight pulses over one was about the same as that provided by turning the background noise down 3.5 db. These results have a rather striking implication: there must be very little fluctuation in the detection process within the auditory system. If there were, the best one of eight looks at the stimulus would be much better than just one look taken at random.

Absolute thresholds of animals.—Ash's review (4) on the sensory capacities of infrahuman animals summarized the product of over 50 papers on animal hearing. The product is hardly commensurate with the quantity of effort, mainly because much of the work suffered from lack of precision of acoustic measurement and from lack of absolute reference intensities. There is, however, a tendency for the sensitivity curves of Ash's graph that summarizes the most important work—determinations of the absolute thresholds of various animals—to follow the rule: animals are less sensitive than man at low frequencies, about the same in the middle range, and more sensitive at high frequencies. [Re high frequencies: In rodents, Schleidt (77) observed reflex responses to sounds ranging up to almost 100,000 c.p.s.] Since the animals were all smaller than man (and had smaller cochleas), this is in line with the implications of Békésy's (8) observations on the physical and mechanical characteristics of the ears of animals. The rat is shown so much less sensitive than man, however, that one would suspect a gross error if Jamison's (47) recent measurements of the rat's threshold did not roughly confirm Ash's curve.

Observations by Antrum & Poggendorf (3) show that, on the basis of power sensitivity, small fish are more sensitive than man at low frequencies, less sensitive at high. This is a reversal of the rule just mentioned, but the fish (having neither air around them nor cochleas within them) do not have the problem of matching impedances that, according to Fletcher, accounts for man's relative insensitivity at low frequencies.

SUBJECTIVE ATTRIBUTES OF SOUND

Just as engineers are beginning to express their results in mels and sones, and even to build meters that read directly in subjective units [Cudworth (25)], psychologists are finding cause for concern about the reliability and/or validity of the subjective scales.

Loudness.—A loudness scale is the relation between the subjective loudness of a sound and its level above threshold (2). Although for a long time it was argued whether or not the subjective magnitudes are measurable, the problem in recent years has settled down to being one of the exact form of the relation, and even that question was regarded as sufficiently well answered [despite the divergence of such results as those of Laird, Taylor & Wille (49)] to warrant the adoption of a standard loudness scale (1). However, Garner (37) recently described the results of a thorough study of half-loudness judgements (on which loudness scales are chiefly based), and his results suggest that we have been talking and calculating, these last few years, with an unwarranted air of precision.

Garner's study showed that the variation among listeners in making half-loudness judgements is great. Comparing the two extreme listeners in the group of 18, he found that while one required only about 7 db attenuation to reduce a 1000-cycle tone to half loudness, the other required about 27 db attenuation. This difference was a stable difference between the listeners; it was not due to error of measurement. Despite the wide range of variation, it was of course possible for Garner to construct a loudness scale. His comparison of that scale with the American Standards Association scale challenges the growing tendency to use loudness scales as through they were meter sticks. At a loudness level of 10 phons, Garner's loudness was 0.2 sone and the ASA loudness was 0.0143 sone. At a loudness level of 100 phons, Garner's loudness was 12.6 sones and the ASA loudness was 90.2 sones. The discrepancy from one end of the scale to the other, therefore, is a factor of (0.2/0.0143)(90.2/12.6), or almost exactly 100.

As a supplement to the method of fractionation (half-loudness judgements), the method of monaural-binaural comparison was used in the construction of most of the loudness scales. This method involves the assumption that a sound heard with two ears is twice as loud as a sound heard by one. But it it? Pollack (71) determined loudness scales for speech, one by fractionation, one by monaural-binaural comparison. At 15 db sound pressure level, one scale has an ordinate of 0.16 sone as against 0.02 for the other scale. At 100 db the corresponding values are about 35 sones and 700 sones. The discrepancy factor[8] here is over 200.

Pollack (70) also determined a loudness scale for white noise. He used half-loudness judgements, monaural-binaural comparisons, and, in addition, a substitution or transfer method in which the noise was matched in loudness to a 1000-cycle tone and the magnitude of the loudness then read from the loudness scale for the tone. The equal loudness matches for a given listener were consistent and repeatable, but differences among listeners were as great as 30 db. At 100 db sound pressure level, the discrepancy between the loudness computed from half-loudness judgements and monaural-binaural comparisons and the loudness derived from the loudness scale for the tone was about 700 sones to 140 sones.

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[8] It is reasonable to suppose that the listener's long-standing habit of paying attention to the meaning of speech might influence in some way his conception of its loudness and pitch. Indeed, observations by Cooper, Liberman & Delattre (23) indicate that some of their synthetic sounds change markedly in subjective character when, as sometimes happens, the listener suddenly starts hearing them as speech after having heard them merely as complex tones. But, if they both get at the same subjective attribute, why should the fractionation and monaural-binaural comparison procedures yield such divergent results for speech?

These evidences of variability do not indicate that loudness is not a legitimate attribute of auditory sensation. They do not disallow the possibility of determining a scale of loudness representative of the central tendency of a population of listeners. On the other hand, it is important to realize how great the differences are among listeners and among loudness scales. In practical work, where the great value of being able to quantify the reactions of human beings tempts one to say, for example, that such-and-such a treatment reduces the loudness of noise by a factor of 5, it makes a real difference whether the 5 is 5 or 25. And in theoretical work, where the great value of being able to accept or reject a theory on the basis of a quantitative prediction tempts one to rest an argument on the evidence, for example, that two ears are twice as loud as one, it makes real difference whether the two is two or the square root of two. Particularly important, I believe, are two notions that are brought back to our attention by the discrepancies among the loudness functions: (*a*) loudness is to be understood probably not so much in relation to any simple neural mechanism [number of nerve impulses reaching the brain in unit time (32, 67), total excitation in an auditory center (19)] as in relation to the development of the concept of loudness in the verbal habit system of the individual; and (*b*) factors such as set, attitude, and expectation are perhaps as important as intensity in determining the subjective reactions of a listener. Perhaps related to this second point, and certainly relevant to the use of the Fletcher-Munson procedure (35) in evaluating industrial noise problems, is Pollack's (68) finding that the loudness of an interrupted noise cannot be calculated from its power density spectrum. A noise may sound louder when it is turned on and off than it does when it is left on all the time.

Pitch.—Apparently expecting better consistency with pitch than the experiments just described found with loudness, Morgan, Garner & Galambos (64) asked the question, "Precisely what is the relation between pitch and intensity?" They found, however, that "no two sets of data were alike. The functions for one ear might go up with intensity while those for another ear might go down." Excellent statistical analysis and display of their data enabled them to show that, in so far as central tendency was concerned, their results confirmed the direction of variation of pitch with intensity of the earlier functions of Stevens (84) and Snow (79)—enabled them to show that without submerging the main result: that everyone has his own, personal pitch versus intensity function.

Pitch has another difficulty. There is not agreement that it is just one attribute. Opposing a duplex conception (28, 54) of pitch, Garner (36) gave an analysis of the difficulty introduced into the discussion of auditory subjective attributes by the fact that the range of frequencies over which we can experience "intermittency" overlaps the range of frequencies over which we experience "pitch." He pointed out that, in other modalities, intermittency is perceived in approximately the same frequency range as in hearing, which fact "should remind us that intermittency can be experienced and that it does not have to be called pitch." Certainly it does not have to be called pitch, for a rose by any other name. . . . The trouble is, we do call pitch—whenever we listen to music in the lower or middle registers or to any other sounds that afford us the opportunity to check up on the basis of our perceptions—the attribute that is related to periodicity or intermittency. What about the attribute that is related to the place of maximum displacement? Well, unless we adopt the terms "tone height" and "chroma" or "buzz" and "body," we call it pitch, too. That is one of the confusing things about the subjective attributes.

HEARING SPEECH AND SPEECH-LIKE SOUNDS

In previous volumes of the *Annual Review of Psychology*, the hearing of speech was treated very briefly. This year there are developments that warrant more extensive description.

Synthetic speech.—A steady vowel sound has a line spectrum consisting of the first 50 or so harmonics of the fundamental frequency. The amplitudes of these harmonic components are governed by the (variable) transmission characteristic of the vocal tract, and it usually turns out that there are three main intervals along the frequency scale in which the amplitudes are relatively high. The concentrations of energy are the formants.

In order to study the effect of varying the characteristics of isolated formants, K. N. Stevens (81, 82) simulated them by applying impulsive excitation to a simple resonant circuit. He measured, for single pulses and for series of about 45 pulses, the differential threshold for formant frequency (i.e., for resonant frequency of the tuned circuit) and for coefficient of damping. As the damping increased, the sensitivity to changes in frequency decreased—more markedly for low-frequency formants than for high-frequency formants, as the relation between damping and bandwidth, considered together with the function relating Fletcher's critical bandwidth to frequency, would lead us to expect. The difference limen for damping was about as large as the differences in damping among actual vowel formants, but the difference limen for frequency was much smaller than the differences that exist between corresponding formants of vowels that are neighbors in the vowel triangle. The latter fact Stevens interpreted as reflecting either (*a*) a considerable factor of safety in speech perception or (*b*) the action, in speech perception, of a part or mode of the auditory system that is different from the part or mode that mediates the discriminations in psychophysical tests.

Approaching actual speech a step closer, Stevens explored the influence of the presence of a second formant upon the discriminability of small changes in the first. There was little degradation except in a case in which both formants were at high frequencies. Stevens has not yet made tests with three formants, but observations with three-formant speech synthesizers indicated that the procedure of synthesizing speech sounds by applying controlled excitation to three variable resonant circuits is reasonable. Two such synthesizers made clearly recognizable vowels and fair consonants.

Fant's work (31) on the theory of speech production is significant for the study of speech perception. Fant analyzed the action of the vocal mechanism in terms of the excitation function (a train of vocal pulses in the case of vowel sounds, fricative noise in the case of some consonants, etc.) and the transmission function of the system of throat and mouth cavities. He showed how the formants, which are basic elements in an acoustical analysis, are related to a few geometrical parameters of the vocal tract. These geometrical parameters give us a new basis for the analysis and description of speech sounds.

In an extension of Fant's work, Kasowski (48) and K. N. Stevens (83) constructed an electrical analogue of the vocal tract, an elaboration of an earlier device built by Dunn (29). It consists of generators of excitation functions and a variable transmission line. The latter consists of 35 cascade filter sections, each of which represents a short length of tube corresponding to a segment of the vocal tract. By adjusting the circuit to produce a clearly recognizable speech sound—it makes good consonants as well as good vowels—one can obtain directly a description of that sound in Fant's terms.

The change in our conception of speech production is similar to the change in our conception of the action of the cochlea. For models consisting of a number of resonators excited in parallel, we are substituting models consisting of a number of resonators connected in cascade, with the excitation traveling down the chain. An important corollary of this change is that we no longer identify a formant with a single resonator (e.g., back cavity of vocal tract), just as we no longer associate a maximum in the displacement of the cochlear partition with the action of the individual segment of the partition that is in resonance with the stimulus frequency.

The transmission-line models are not yet far enough developed, however, to rival the parallel-resonator models when it comes to flexibility and convenience of use. The sound spectrograph is still the basic analytic tool, and its complement, a synthesizer of sound waves from spectrograms has opened up extremely interesting possibilities in the study of speech perception. This device, developed in somewhat different forms by Cooper and his co-workers (21, 22) and by Vilbig (88), makes it possible to produce arbitrary revisions of the intensity-frequency-time pattern of a sound, or even to synthesize an entirely new sound by painting on a transparent strip of film.

Playing back synthetic spectrograms, Liberman, Delattre & Cooper (53) found that a sound usually heard as "p" when followed by "i" or "u" was usually heard as "k" when followed by "a." If confirmed in tests with actual speech, this finding will upset one of the basic notions about the phoneme. Whether regarded as a class, a target, a bundle of features, or the smallest linguistic unit critical to the identification of a morpheme, the phoneme has quite generally had associated with it the idea that its determining features were within. Here is a case in which a critical condition for the identification of a consonant resides clearly outside the consonant.

Cooper, Liberman & Borst (22) explored the interconversion of audible and visible patterns somewhat simpler and more amenable to control and specification than speech. They painted circles, squares, triangles, etc., on the film and had subjects note similarities and differences among the audible, as well as the visible, patterns. Some of the invariances that characterized the visual perception also appeared to characterize the auditory perception, but there were exceptions. All the triangles had something in common, aurally as well as visually, but a visual diamond and a visual square were much more alike than their auditory counterparts.

Distorted speech.—In a study of public address systems, Beranek, Radford, Kessler & Wiesner (14) found that naturalness was not adversely affected if the frequency components of speech below 400 c.p.s. were attenuated. On the other hand, intelligibility was not impaired, even in highly reverberant auditoriums, if the low-frequency components were amplified, provided the high-frequency response was good out to 4000 c.p.s. In extending these results, already established for headset listening, to auditoriums, they developed a useful variation of the articulation test: listeners seated in the audience wrote down the final words of the sentences of the speech being delivered, and their records were scored against tape recordings of the signal picked up by the microphone.

In an effort to dissect out of the problem of room acoustics a piece amenable to laboratory measurement, Haas (38) studied the influence of single echoes upon intelligibility. The echoes were delayed by various intervals and were amplified or attenuated by controlled amounts relative to the direct speech wave. When the interval was less than 30 msec., the echo made the speech sound louder and changed the timbre, but was not perceptible as an echo and had no effect upon intelligibility. However, longer intervals yielded detrimental effects upon intelligibility and, at a critical interval that depended upon the intensity of the echo and other factors, the speech became practically unintelligible.

Auditory control of speaking.—Continuing interest in the roles played by hearing in the learning of speech, the maintenance of speech habits, and in the adaptation of speech to ambient acoustic conditions is reflected in papers by Huizing & Pollack (45), Hudgins (43), and Hardy, Pauls & Bordley (39). And a systematic extension of the Bell Telephone Laboratories' study of the "side-tone reflex" is under way in a series of experiments by Black and his co-workers (15, 16, 17, 55, 56). But the dramatic development in auditory control of speaking is the delayed feedback effect.

Delaying the side-tone, as almost everyone now knows, disrupts the talker's speech. The talker blocks, slurs, stretches out his speech sounds until he hears them come back to his ears. This effect was noticed almost simultaneously all over the country when tape recorders with delay in the monitoring channel made their appearance. However, Lee (51, 52), Black (17), and Fairbanks & Jaeger (30) had already been studying the effect with apparatus that provided variable delay. Their results indicate that the disruption becomes marked (if the side-tone gain is high enough) as the delay is increased to about 0.1 sec. It is not evident from the data that there is a clear maximum of disruption, but the interval of critical delays may be related to the durations of speech units or to the much-contraverted perceptual time base. Implications of the effect for stuttering, stammering, expressive aphasia, and other abnormalities involving speech have of course been suggested. Sufficient data are not yet available for one to evaluate the suggestions or to put together a definite picture of the delayed feedback effect, but the study is proceeding, and it appears that it may in due course lead to an understanding of what is certainly one of the most interesting biological feedback mechanisms.

A practical application of delayed feedback has already been made. Azzi (5) and Tiffany & Hanley (87) found that, since persons with normal hearing cannot entirely overcome the disruptive effect, a delayed side-tone test made an excellent trap for malingerers.

Theory of speech perception.—The progress in the last year toward a theory of speech perception was the sharpening of three ideas.

(*a*) Cherry (20) considered the perception of speech from a communicacation engineer's point of view and emphasized the inductive, statistical nature of the process. His functional model is a sequential decision-maker, operating on the principle of Bayes' Theorem in the way described by Woodward & Davies (90). The noisy received signal consists of elements in sequence, the linguist's phons. Each phon corresponds to, and should be identified by the listener with, a phoneme. The elements are chained sequentially under the influence of conditional probabilities. The process of reception (inverse-probability calculation) therefore takes into account both the new evidence and the a priori information contained in the statistics of the already received signal. As information continues to come in, the listener narrows down the possibilities until there is a sufficiently strong concentration of likelihood about one phoneme or sequence of phonemes to warrant the decision that it is the correct one. It is then stored, and helps to condition the calculations for the next decision. Beyond the stage of deciding among phonemes comes a second stage of deciding upon larger units of the message. The process is again essentially a calculation of what is most likely in view of the a priori probabilities (which may be only rough estimates or rankings) and the incoming evidence.

(*b*) Jakobson, Fant & Halle (46) elucidated the significance for speech analysis of the distinctive-feature theory of the phoneme. According to that theory, somewhat oversimplified, a phoneme is a set of binary distinctions or oppositions. For example, the "k" in king is not vocalic but consonantal, compact not diffuse, not nasal but oral, tense not lax, not continuant but interrupted, and not strident but mellow. The "k" can therefore be represented by the binary digits 010100. It is different from every other phoneme in at least one digit (distinctive feature). Although Jakobson, Fant & Halle did not explicitly formulate a theory of the perceptual process, the implication is clear that one of the early stages of the process should involve detections of the distinctions, and that the identification of a phoneme should rest on the bringing together of the (approximately six) elementary decisions. One might call this a teletype theory of phoneme recognition, for conventional teletype receivers operate in almost precisely the way just described.

(*c*) Broadly speaking, speech perception (as well as other perceptual processes) seems to involve the comparison of a received pattern with stored, standard patterns. There are two basic ways of making the comparison. The received pattern can be held up against the standard so that the degree of correspondence can be measured, or it can be forced into or through the standard so that the degree to which it fits, or is tuned to, the standard can be determined. The first notion is closely related to the concept of correlation, the second to the concept of matched filtering and the convolution integral. The implication for auditory theory is that part of the nervous system must function in one of these two ways in recognizing the elements of speech and also in comprehending ideas. Examination of the properties of the two models suggests that the recognition of phonemes might involve matched filtering whereas the comprehension of ideas might involve correlation.

OTHER DEVELOPMENTS

Important work has been done on several topics I have not tried to cover. Problems of industrial and military noise, particularly jet aircraft noise, are becoming critical, and some excellent studies have appeared. Now is not the right time to summarize the picture, however; it will be much more complete next year or the year after. A similar situation exists in the application of information theory to psychophysics. There is a start, and there is a promise of much to come, but there is not yet a complete picture. In audiometry there were many papers, and in otology even more. There were valuable articles on auditory fatigue, on binaural hearing, on sensory prosthesis, on recruitment, and on noncochlear, nonspeech auditory theory.

Finally, I should like to mention one journal and two books. A new, international journal, *Acustica*, made its appearance. Associated with it is a German supplement, *Akustische Beihefte*. They will do much to get the backlog of European contributions to audition (40) into print. Miller's *Language and Communication* (62) brings together in one place contributions fundamental to a broad understanding of hearing, from phonetics, psychoacoustics, statistics and communication theory, logic, the psychology of individual differences, developmental psychology, the psychology of learning, and social psychology. In addition, it develops in detail the important role of contextual determination in speech production and perception. Stetson's *Motor Phonetics* (80) makes available a wealth of little known work on the production of speech, much of which is clearly significant in relation to the understanding of speech.

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